Approaches for the Design of Ceramic Gun Barrels

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APPROACHES FOR THE DESIGN OF CERAMIC GUN BARRELS

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ABSTRACT

The Army continues to be challenged to maintain the life of its cannons while introducing more robust propelling charges to provide increased performance. Audino (2004) reported declining cannon life in large caliber cannons with the introduction of each new projectile such that the current M256 cannon can fire less than 300 M829A3 rounds before being condemned.

Over the past decade, substantial improvements in the robustness and consistency of quality of structural ceramics and the development of improved predictive methods for the failure of said materials resulted in the Army Research Laboratory investigating the utility of this class of materials for use in modern high velocity cannons. This paper reports on the evaluation of the structural ceramics investigated and the design approaches implemented to utilize them in as a liner material for a gun barrel.

1. INTRODUCTION

Army propellant designers continue to press forward with the use of more energetic materials to improve the muzzle velocity of fired projectiles and subsequently their performance on target. Typically, these more energetic propellants operate at higher flame temperatures and result in more thermal energy being imparted on the bore surface. The combination of elevated temperature and high velocity gas wash over the surface exasperate the problem of maintaining cannon life for gun barrel designers.

Much of the research to date has focused on protective coatings applied directly to the bore surface. The problem with such an approach is maintaining sufficient adhesion between the coating material and the steel barrel substrate. Chromed-cannons have been successfully employed but after repeated firings, the chrome coating begins to crack and eventually flake off. This exposes the steel substrate and then quickly degrades in the harsh environment of propellant gas products.

An alternative for extending barrel life is to introduce a ceramic liner to provide a wear and erosion resistant material as the bore surface. There have been several previous Army programs that have looked at incorporating ceramics, none of which resulted in a workable design (Katz, 1996). Due to the limitations of ceramics under tensile load, it has been recognized that imparting a state of pre-compression to the structural ceramic is critical to surviving the loads encountered during a ballistic firing.

The Army Research Laboratory undertook an effort to investigate commercially available, structural ceramics and ascertain their viability as liners for high-pressure cannons. The effort used a three-pronged approach that included: 1) extensive material characterization; 2) incorporation of a probabilistic design approach to accurately represent the response of ceramics in the cannon application; 3) development of a sheathing method to provide the needed multi-axial stress required to survive the ballistic event.

2. CERAMIC MATERIAL ASSESSMENT

Eight commercial off the shelf (COTS) ceramics were considered including aluminum oxide (Al_2O_3), zirconia (ZrO_2), silicon nitride (Si_3N_4), silicon carbide (SiC), and silicon aluminum oxy-nitride (SiAlON). Traditional sintering methods were used to fabricate all materials, with the exception of the SiAlON which was subjected to a post-sintering hot isostatic pressing (HIP) process. A wide range of mechanical and thermal properties were determined on these candidate ceramics. Details on the test procedures used and the properties determined have previously been published by Swab et al (2005). The Si_3N_4 ceramics and the SiAlON were, on average, the strongest materials tested but the Weibull modulus determination of each indicated a strength variability in the materials. Thermal testing showed that the oxides had the largest average coefficient of thermal expansion (CTE) followed by the SiC's and then the nitrides. The SiC's had the highest thermal conductivity, with the Al_2O_3, Si_3N_4 and the SiAlON materials well below this

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value. The zirconia had the lowest thermal conductivity of the ceramics evaluated.

To investigate the ceramics in a representative erosion environment, they were subjected to several tests to simulate the interior ballistic conditions found in gun systems. Standard ballistic tests using a 37mm blow-out gun (Stobie et al 1982) and a closed bomb chamber (Clemins 1975) were used to expose the ceramics to representative conditions (temperature, pressure, etc.) created using JA-2 propellant. In the blow-out gun test, the ceramic was exposed to a single shot then cleaned and weighed. The mass loss was determined and compared to results from previous research on a typical gun steel. Depending on the outcome of this exposure, ceramics that performed well were subjected to additional shots with the mass loss determined after each shot. Two sets of closed bomb exposures were conducted on each ceramic. One set was subjected to a single closed bomb test and the second set to 10 consecutive tests. These specimens were used to examine ceramic/propellant interactions. Results of these tests showed that both of the Si_3N_4 ceramics and the SiAlON performed the best. These ceramics exhibited a minimal but consistent mass loss with each blow-out test and that a porous glassy layer began to form on the specimen. This glassy layer also formed on the specimens subjected to the closed bomb testing. This layer appears to form due to passive oxidation which slows the oxidation kinetics and results in the formation of a protective oxide layer at the surface.

The Al_2O_3 exhibited extensive cracking after a single blow-out test and the closed bomb specimens completely fractured after only seven exposures. The zirconia exhibited increasing mass loss with each blow-out test and a significant amount of cracking during the closed bomb tests. The mass loss and cracking was attributed to the tetragonal to monoclinic phase transformation that occurs when this material is exposed to elevated temperatures. All of the SiC ceramics had extensive mass loss due to cracking after a single blow-out test. However, they survived the 10 closed bomb exposures with an increase in surface roughness and the formation of a glassy layer on the surface due to oxidation.

One of the Si_3N_4 materials and the SiAlON were subjected to the temperature and pressure profile representative of the conditions experienced in an 120-mm cannon, at the location of the most severe erosion, using the vented erosion simulator (VES). In this test a cannon propellant is ignited and allowed to vent through a nozzle that contains a ceramic insert. The ceramic is then analyzed to assess the resulting damage. This test methodology is further described by Underwood et al (2004).

Four specimens of each ceramic were subjected to 1, 2, 5 and 12 VES shots to capture the damage evolution process. Analysis of the exposed surface of the ceramic insert after 1 VES shot indicates that an oxide layer is forming, similar to the layer that formed on the closed bomb specimens. This layer does not uniformly cover the entire surface as there are three morphologically distinct "layers" present at the exhaust end. It is believed that these three layers are compositionally the same but that they look different since varying amounts of the layer were removed during the exposure.

Two additional specimens of the Si_3N_4 material were scheduled to be exposed to a maximum of 100 VES shots each. After every 10 shots the ceramic was removed from the fixture, cleaned and weighed to determine the mass loss due to exposure. The first specimen survived 44 shots and the second specimen a total of 94 shots. In both cases testing was terminated not because of excessive damage to the ceramic but because a small corner chip appeared at the exhaust end of the insert which imperiled the steel test fixture. The mass lass for each specimen averaged approximately 10mg per 10 shot sequence. This consistent, low mass loss rate shows the utility of ceramics in resisting erosion during a combustion event. Figure 1 shows the progression of mass loss over the duration of the two tests.

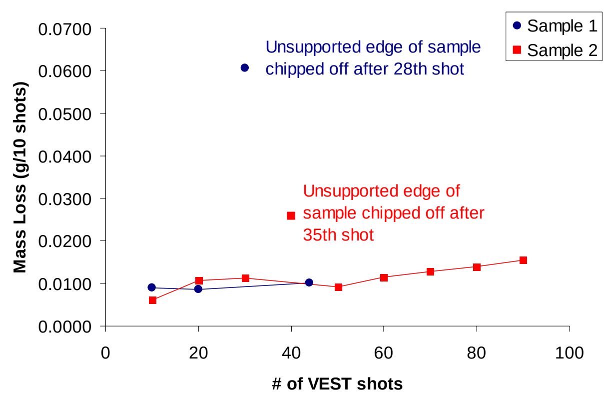

Figure 1 – Mass loss per shot of ceramic specimens in vented erosion simulator testing (VEST)

3. PROBABILISTIC MODELING

Two modeling approaches were used for this program. An analytic model was developed for guiding design and parametric studies of materials and to simulate fabrication approaches. A numerical ceramic gun barrel model was developed that incorporated the NASA CARES code (2005) for predicting the ceramic response using probabilistic mechanics. The model accounts for design variables such as the material properties of the ceramic liner and the sheathing, the weapon system ballistic conditions, and the thermal conditions due to any arbitrary firing schedule. The materials were then evaluated for a range of weapon systems - 5.56mm small arms, 25mm medium caliber, 120mm tank cannon, and 155-mm artillery.

The model development coincided with experimental testing to provide a means for verification. Initial tests were of unsheathed or blank ceramic tubes. Due to the variable nature of the strength values, the predictions provide ranges where there is a high probability of failure, as opposed to a specific value. Numerous tests were conducted to determine the Weibull properties of several candidate ceramic materials (Swab et al., 2005). The Weibull volume, m_v, and area, m_a parameters are listed in Table 1 with other material properties for two of the silicon nitride materials used for experimental testing.

Table 1 – Average material properties for two silicon nitride compositions

Property	**SN47**	**SN5P**
Modulus (GPa)	326	313
Poisson's Ratio	0.26	0.25
CTE (ppm/°C)	3.18	3.19
σ_{oV} (MPa*mm$^{3/m}$)	1653	887
m_v	9.4	16.9
σ_{oA} (MPa*mm$^{2/m}$)	1047	949
m_A	13.7	12.3

The experimental tests on the ceramics characterized volumetric flaws and two types of surface flaws on the outer surface. No experiments were conducted to characterize flaws on the inner surface. In order to get around this lack of information, the inner surface was treated as if it contains identical flaw populations as the outer surface. This assumption is not ideal, but allows for high and low estimates of the probability of failure for a given sample. In Figure 2 there are two curves showing the probability of failure for the SN47 silicon nitride tube (24 inner diameter (ID) x 33mm outer diameter (OD) x 50mm long). The lower estimate is for the combined probability of failure for surface and volumetric flaws. The higher estimate was calculated using a probability of failure due to volumetric flaws only. In between the predicted curves are the experimental data points for burst pressure for different silicon nitride tubes. At the time of this publication there have been eight tests of the unsheathed tubes. The results have been ranked as described in the ASTM standard (ASTM C1239-00, 2004) for determining the Weibull characteristic. Even though there are a small number of data points, the data appears to be well bracketed by the prediction curves.

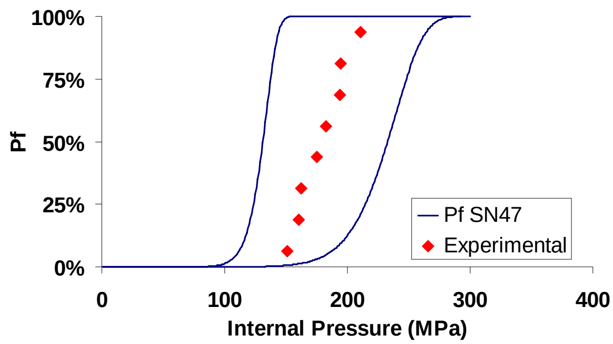

Figure 2 - High and low predictions for the burst pressure for unsheathed SN47 silicon nitride tube.

The model was next used to predict the burst pressure for a sheathed ceramic tube. Several sheathed specimens were fabricated using high tension filament winding to create a composite sheath directly onto the ceramic tubes. A plot showing the range of predicted burst pressures for one of the silicon nitride tubes is in Figure 3. The two different prediction curves for the different assumptions are shown, while the failure pressure range is highlighted on the plot. Again the experimental burst data closely matched model predictions.

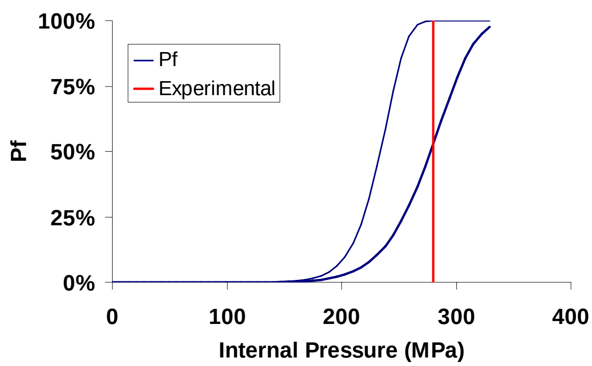

Figure 3 - High and low predictions for the burst pressure for a filament wound composite sheathed silicon nitride tube (SN47).

Further development of the experimental tests has progressed to ballistic simulation via live firing. Figure 4 shows a 200mm specimen with a bonded end-cap for use in a ballistic fixture used to mate the composite wrapped ceramic tube to a gun chamber. Special projectiles were developed to fit within the 24mm ID, and varying propellant charges were used to incrementally subject the barrel to higher pressure loadings. In Figure 5, the model predictions for the probability of failure are plotted against the pressure produced in the ballistic test fixture. The sample survived progressively increased firing pressures, but failed the 262 MPa test shot. From the progressive testing, the actual failure pressure was in the range of 224 to 262 MPa (32.5 – 38.0 ksi) as highlighted in Figure 5. This agrees with the predicted failure range.

Figure 4 – Overwrapped ceramic tube for ballistic testing.

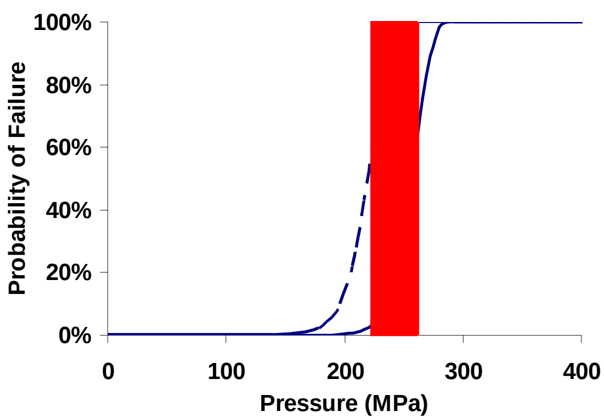

Figure 5 - High and low predictions for a composite/silicon nitride tube (SN5P) in a ballistic test fixture - the vertical red bar indicates the sample failed between 224 MPa (32 ksi) and 262MPa (38 ksi).

Model results can be displayed in the form of failure surfaces plots that map regions of probability of failure of the gun system as a function of input variables. An example failure surface plot is shown in Figure 6 for a 5.56mm gun comprised of a ceramic liner with a shrink-fitted steel sheath and a fixed inner and outer diameter. In this plot, the blue region indicates the best probability of survival, less than 1 in 1 billion. Hence the best design should have a liner thickness with approximately 25% of the total wall thickness and should be have a pre-stress equivalent to that provided by a 0.0035 in interference between the steel sheath and the ceramic liner.

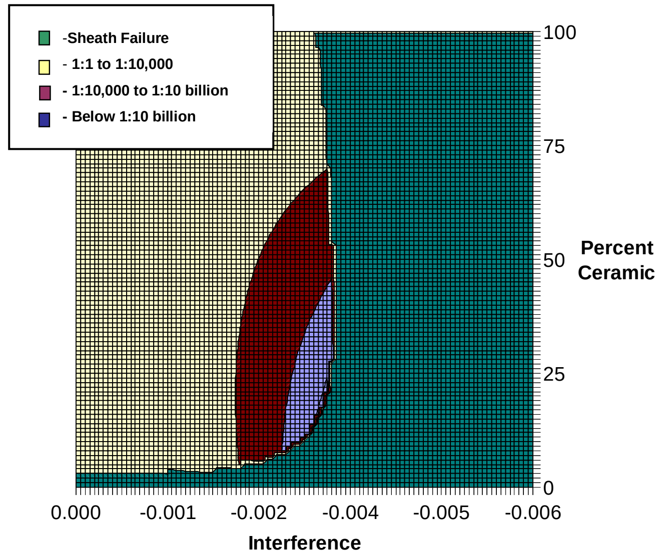

Figure 6. Failure surface plot of a sheathed ceramic tube

4. CONFINEMENT SCHEMES

4.1 Direct Overwrapping

Approaches to sheathing the ceramic liners evolved from simple to rather complex assemblies. As shown in Figure 4, the initial approach was to filament wind high-strength carbon fiber directly onto the outer diameter of the ceramic tubes with the filament subjected to the highest tension possible during winding. Compared to conventional pre-stress methods for tubes (e.g., thermal shrink-fit and press-fit), this so-called "direct-overwrap" method requires fewer components and fixturing and thus is a simpler method. The compressive radial stress on the OD of the ceramic tubes effectively strengthened such specimens to levels sufficient to statistically distinguish them from unsheathed specimens. As such, quasi-static burst tests of specimens fabricated with this approach served to validate the strength model. This modeling and experimentation also provided insight to the limits of the direct overwrapping technique. Figure 7 shows compressive hoop strain data taken at the inner diameter of a hollow aluminum test mandrel that was subjected to high-tension direct overwrapping. The salient feature of this strain data is the diminishing rate of strain-per-layer after six to eight layers have been deposited—despite all layers being deposited under the same level of fiber tension. This diminishing return is due to the fact that previously deposited layers react against subsequently-deposited layers.

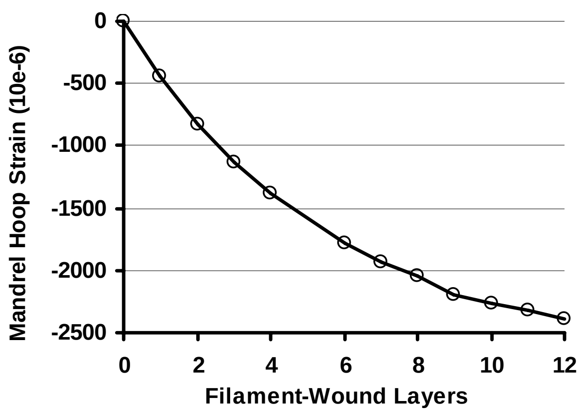

Figure 7. Compressive hoop strain on the ID of a hollow aluminum mandrel used to evaluate high-tension winding.

4.2 Axial Confinement

Axial tensile stresses that arise during the manufacture and service of ceramic-lined barrels have been cited by many researchers as the primary hurdle in sheathing design (D'Andrea et al., 1978; Stephan and Rosenfield, 1982; Katz, 1996). With this axial stress problem in mind, the first approach to imparting axial prestress into specimens to be tested under ballistic conditions was to provide axial reinforcement with external fixturing, instead of attempting to build axial pre-stress into the free-standing specimen with some specific overwrap architecture. Specimens that were fitted with direct-overwrap sheaths (i.e., radial pre-stress only) were installed into a ballistic fixture that incorporated a muzzle-end cap and retaining bolts (Figure 8) to axially compress specimens prior to firing.

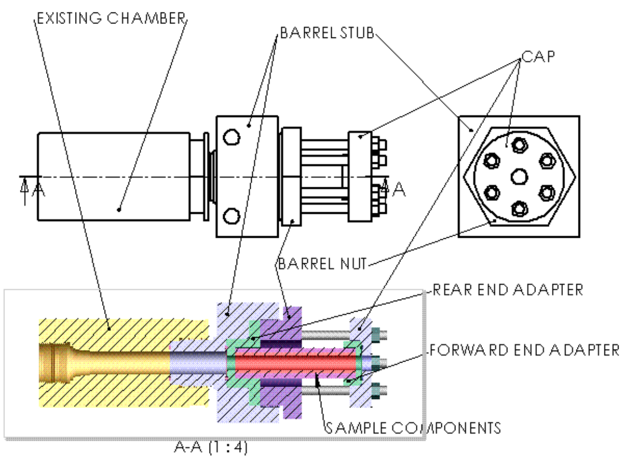

Figure 8. Ballistic test fixture with axial pre-stress components.

The testing protocol for these specimens was to start at a low chamber pressure of 140 MPa (20 kpsi) and then increase the propellant charge in 20-35 MPa (3-5 kpsi) increments until a crack was observed in the specimen. Axially-oriented cracks were observed for all specimens that were tested of this type, indicating that hoop stress was dominant. Like the quasi-static specimen tests described in Section 3, the burst data served to validate the probabilistic model. The burst pressures of approximately 290 MPa (42 kpsi) were significantly lower than the goal of 450 MPa (65 kpsi) defined at the start of the program. Thus, higher-performance methods for imparting radial pre-stress were needed.

4.3 Multiaxial Confinement

A multiaxial confinement design was developed that incorporated a permanent steel sleeve to provide axial pre-stress by tightening two steel nuts at either end of the ceramic sleeve (see Figure 9). A thin layer of aluminum was applied to the OD of the ceramic using Supersonic Particle Deposition (SPD). This thin layer served to mitigate point contact stresses between the steel sleeve and the ceramic. The fit between the ceramic liner and the steel sleeve in this specimen type was a slip-fit at room temperature. The OD of the steel sleeve was tapered and a second steel sleeve with a matching taper and radial interference on the ID was pressed on to the assembly to provide radial pre-stress.

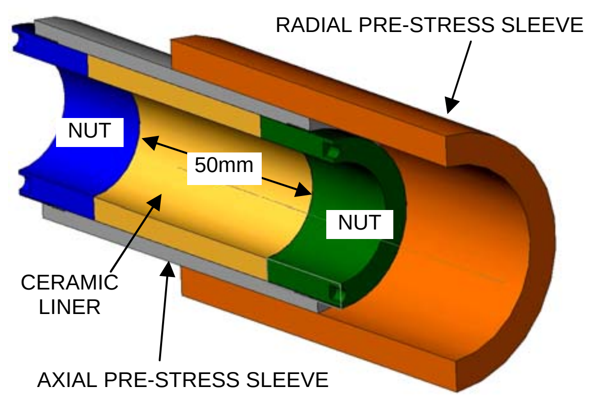

Figure 9. Multiaxial confinement test specimen.

Two specimens of this type were fabricated and tested under quasi-static conditions. The burst pressures from both specimens were significantly lower than predicted. Close inspection of scans of the bore surface recorded prior to testing showed that the specimens exhibited small axially-oriented cracks. These cracks may have been introduced when the 50-mm long liners were cut from the 200-mm parent tube.

4.4 Multiaxial Confinement with Composite Press-fit

Carbon-fiber epoxy-matrix composite press-fits were investigated for their capacity to generate high levels of radial prestress. The highest-strength commercially available fiber, Toray T1000, was used to fabricate several types of composite sheaths. These sheaths were press-fitted over steel mandrels that were instrumented with strain gages to measure sheathing pressure. Two fiber architectures were investigated: a compound helical layup $[\pm 10_2/\pm 45/\pm 82_{13}]$; and a cross-ply layup $[90/0/90_{25}/0/90]$. These architectures were chosen in an attempt to maximize hoop direction reinforcement (for hoop strength and stiffness), while maintaining sufficient axial strength and stiffness to survive axial press-fit loads, while achieving a high level of through-thickness (radial) strength. The helical architectures did not perform well, achieving a maximum sheathing pressure of only 45 MPa (6.5 kpsi) before breaking. Details of the experiments on the helical ply press-fit sheaths are given elsewhere (Emerson et al., 2006). The cross ply architecture performed much better, achieving 240 MPa (35 kpsi) of sheathing pressure and remaining intact.

The sheathing design being evaluated in current experiments uses the axial-prestress component design from Section 4.3 and the cross-ply composite press-fit sheathing mentioned above. A cross section schematic of specimen is shown in Figure 10. The stand-alone specimen incorporates a 200-mm liner and will be tested under ballistic conditions. The OD of the liner has been arc-sprayed with a layer of zinc. This layer serves to mitigate point stresses between the ceramic and the steel sleeve. The zinc layer was machined to a radial thickness of approximately 0.18-mm (0.007-in). The steel sleeve is thermally shrink-fitted over this ceramic/liner/zinc with 0.025-mm (0.001 in) diametral interference.

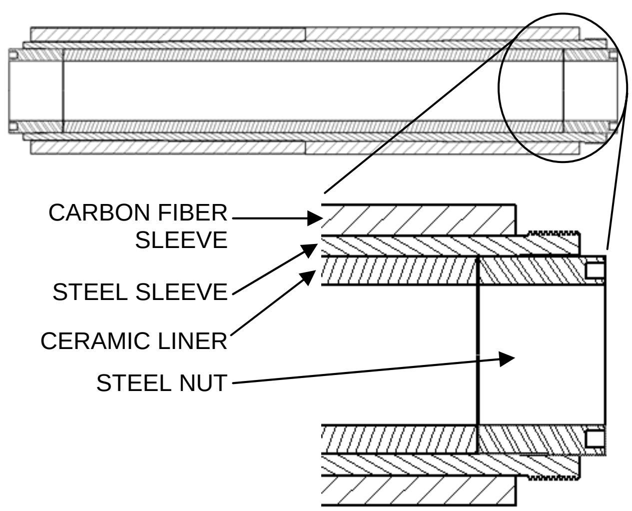

Figure 10. Cross-section schematic of the current specimen design.

Based on the findings from earlier experiments, (Emerson et al., 2005) it is necessary to cut the press-fit sheaths into several short-length sheaths and press each one individually. Otherwise, the friction forces from one long sheath require press forces that exceed the strength of the composite.

CONCLUSIONS

The use of probabilistic modeling tools, with well characterized material data has defined the structural requirements for a compound gun assembly with a ceramic liner. The model can be used over a range of calibers and a variety of materials.

Given the load carrying capacity of the structure, several different approaches such as direct filament wound overwrap or shrink and press fit assemblies have been shown to provide various levels of required compressive pre-stress. These methods can be tailored to provide the required stress states defined by the probabilistic models and give some flexibility to meet thermal and volumetric constraints for a given caliber cannon.

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Ceramics offer numerous advantages for consideration in gun barrel applications

Generic Ceramic Properties

- High temperature capability
- Low density
- Superior wear resistance

War Fighter Payoff

- 50% ⇑ in barrel life with sustained accuracy
- 20% ⇑ in muzzle KE
- 5-25% weight ⇓ (per unit length of barrel)

Enabling Technology

- Higher energy propellants
- High pressures more viable

Eight commercial material candidates

- **All materials are off-the-shelf technologies**
- **No material development was planned**

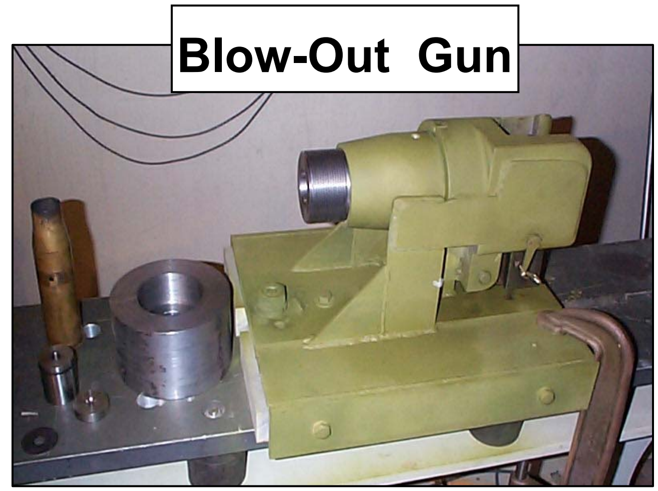
Material	Vendor	Vendor Code
Al_2O_3	CoorsTek	AD995
ZrO_2	CoorsTek	Ce-TZP
SiC	Saint-Gobain	Enhanced Hexoloy SA
SiC	Saint-Gobain	LPS Hexoloy SA
SiC	Ceradyne	146-5S
Si_3N_4	Ceradyne	147-31N
Si_3N_4	Kyocera	SN235P
SiAlON	Kennametal	TK4

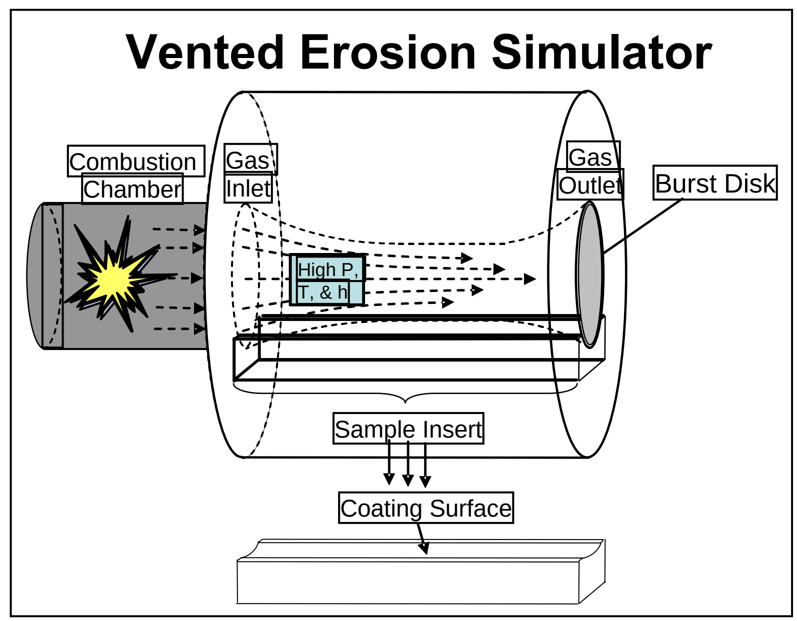
Thermo-mechanical characterization

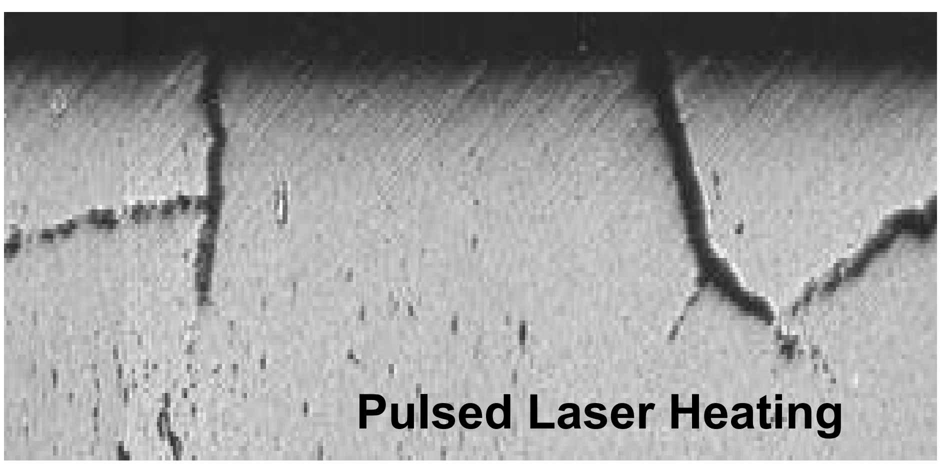
- Strength – Tension and Compression at RT and 700°C
- Dynamic Flexure
- Fractography and Weibull Analysis
- Fracture Toughness
- Hot Hardness - Vickers at 300g (RT to 1400°C)
- Elastic Properties (RT to 1400°C)
- Thermal Properties (RT to 1000°C) - CTE, Heat Capacity, and Thermal Conductivity
- Erosion Resistance

Erosion assessment methods

- **Blow-out Gun – ARL**
  - **Extreme condition erosion test**
- **Closed Bomb Test – ARL**
  - **Examine propellant gas-ceramic chemical interactions**
- **Vented Erosion Simulator (VES) – Benet**
  - **Simulates the 120mm system IB conditions**
- **Pulsed Laser Heating – Benet**
  - **Capable of inducing thermal shock damage similar to that created during an IB event**

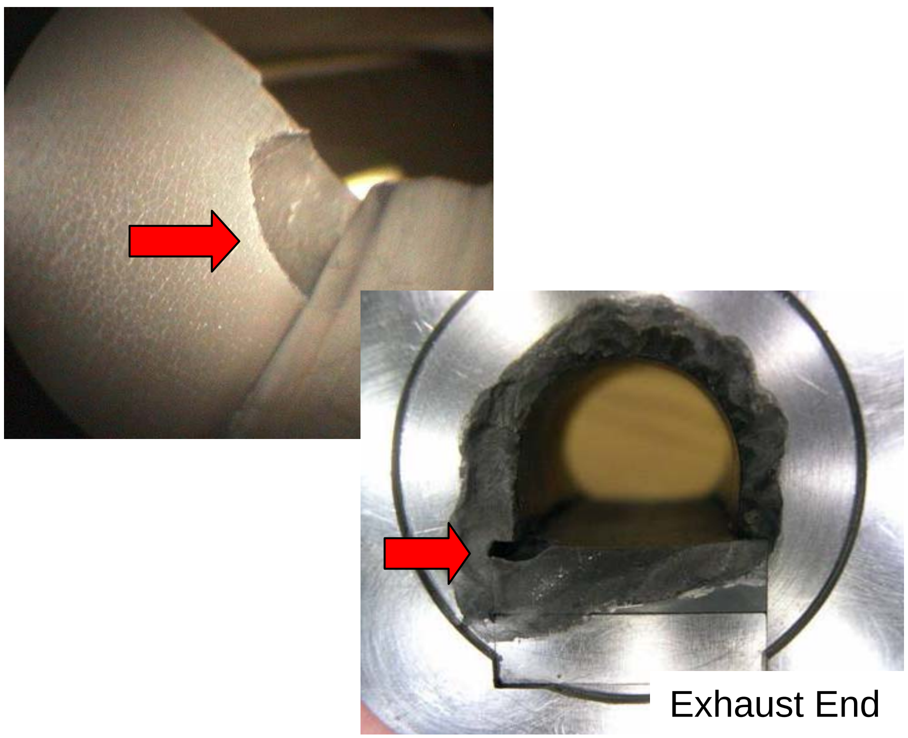




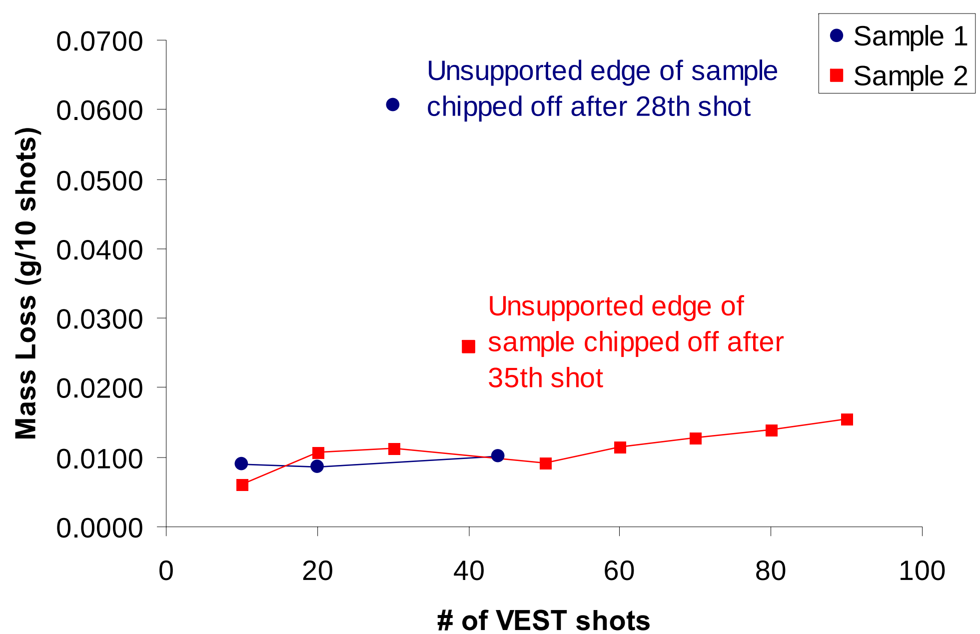


VES closest match to large caliber tank gun environment

- **SN5P: 100 rounds exposure, measure mass loss every 10 rounds**
- **Terminated after 44 and 94 rounds due to potential damage to the VES fixtures**



Exhaust End



"Pros and Cons" of ceramics for gun barrel liners

Pros

- Low erosion rates
- Lightweight

Cons

- Brittle
- Low fracture toughness
- Large variability in tensile strength

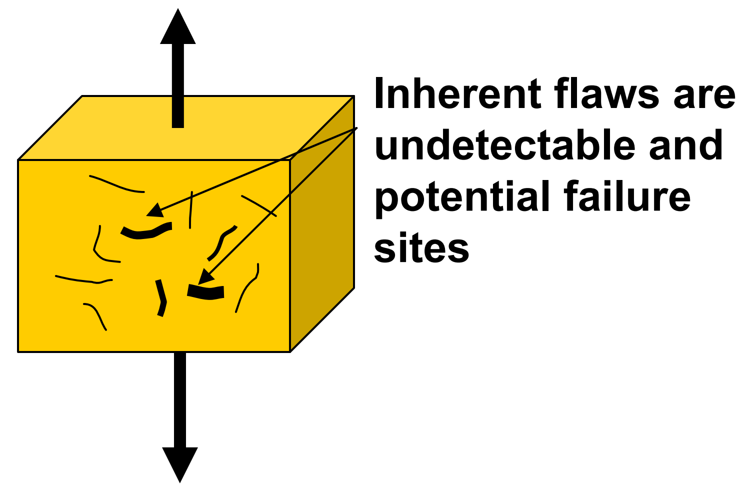
- New modeling and failure prediction approaches are required to design a ceramic lined barrel
- Ceramic liners require compressive pre-stress

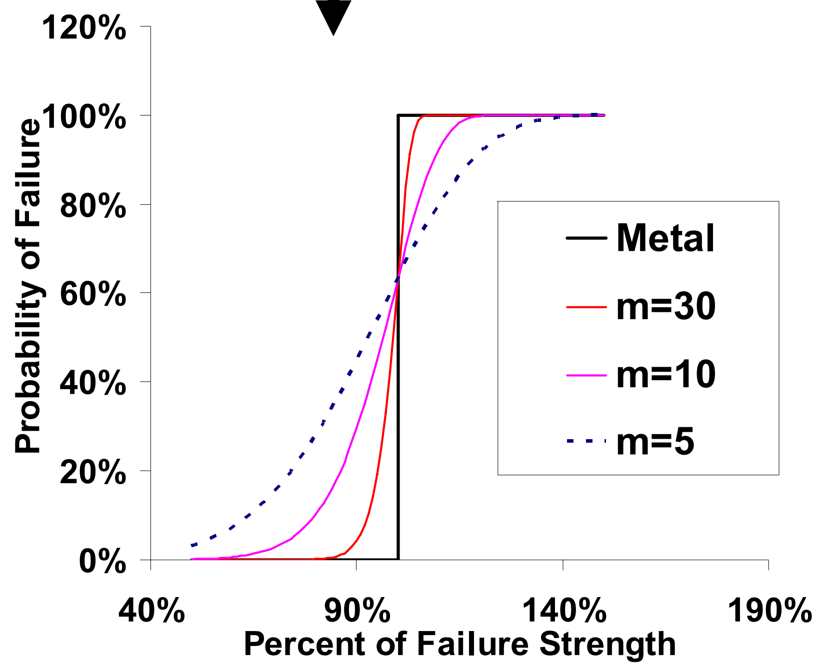
Probabilistic methods necessary to design with brittle materials

- Ceramics can support tensile load, but are subject to large scatter in the observed strength
  - Failure initiates at random flaw sites in the material
  - Failure strengths determined for critical flaws
- Weibull statistics are used to incorporate this information into design parameters

$$P_f = 1 - e^{-\int \left(\frac{\sigma}{\sigma_o} \right)^m dV}$$

P_f = Weibull Probability of Failure
σ = Applied Stress
σ_o = Characteristic Strength
m =Weibull Modulus



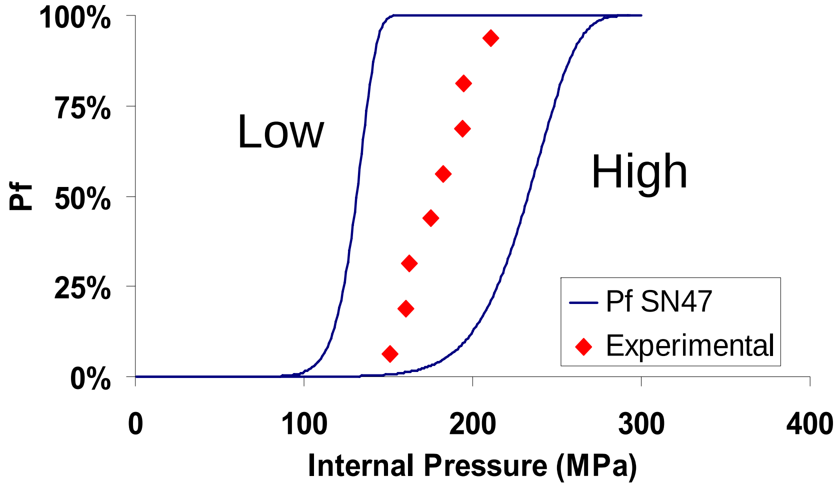


Internal pressure testing

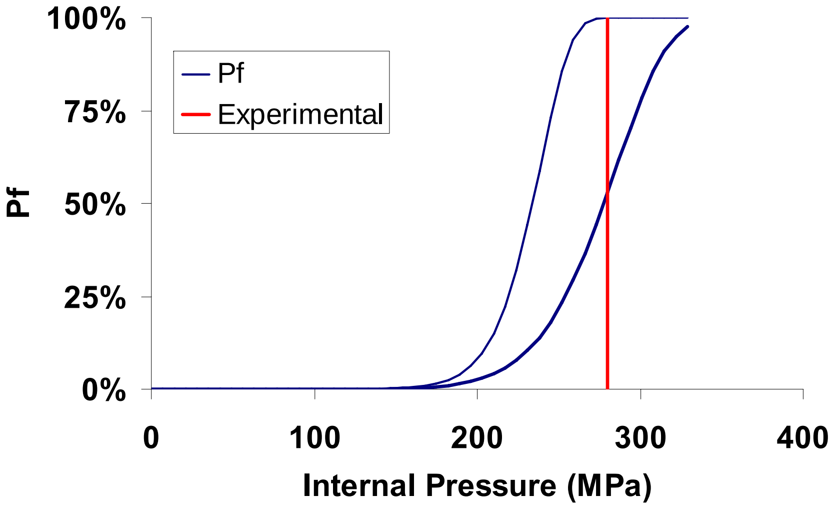
- Upper and lower bounds of model predictions
  - <u>Upper</u> - considers volumetric flaws only
  - <u>Lower</u> - considers volumetric and surface flaws

Un-sheathed burst specimen

SN47 Unsheathed

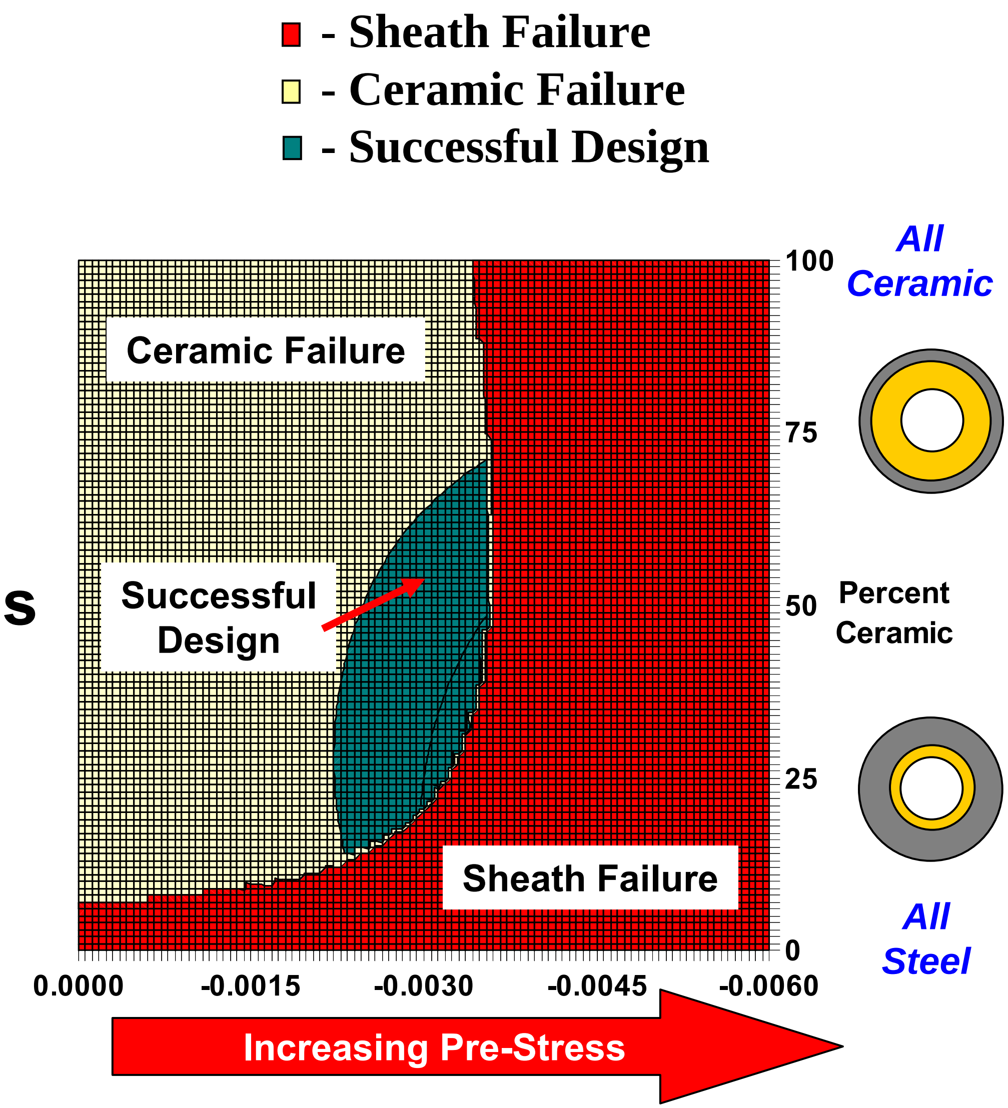


SN47 + Composite Sheath



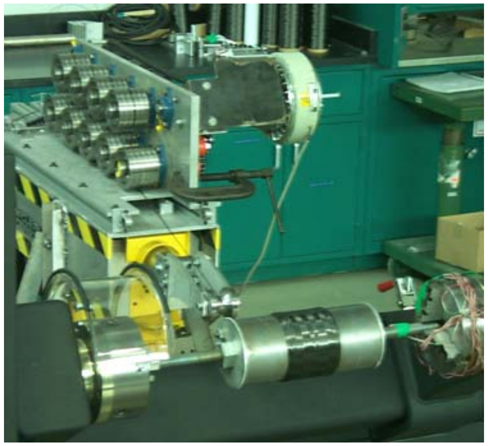
Failure surface plots

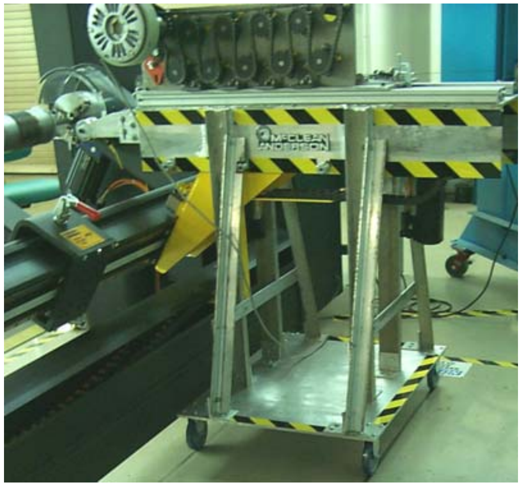
- The model is applied to search for successful designs for different gun/cannon tubes
- Failure surface plots illustrate the effects of varying ceramic thickness and pre-stress level for a pressurized tube
- Allows for quick visualization of different design concepts



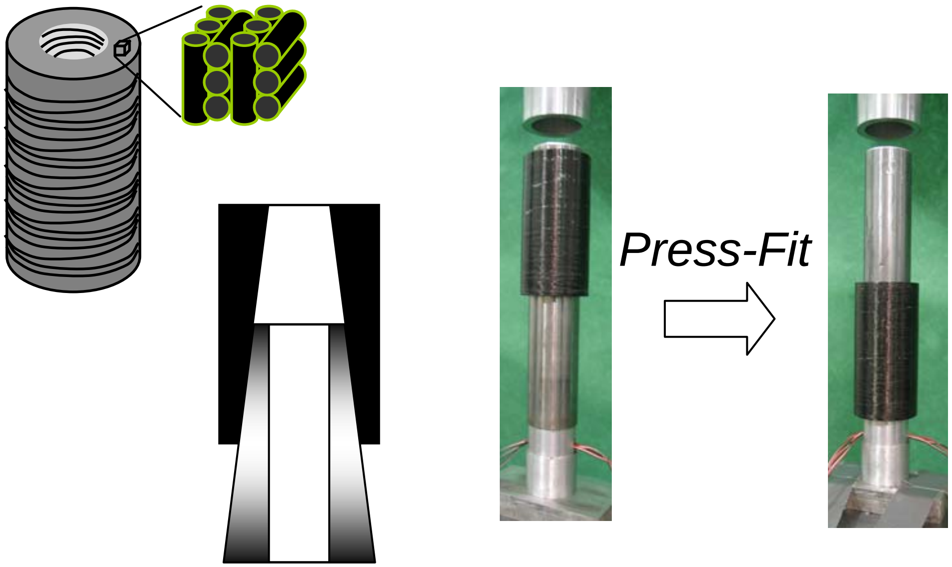
Pre-stress methods

- High tension filament winding
  - simplest procedure
  - capable of only moderate levels of pre-stress



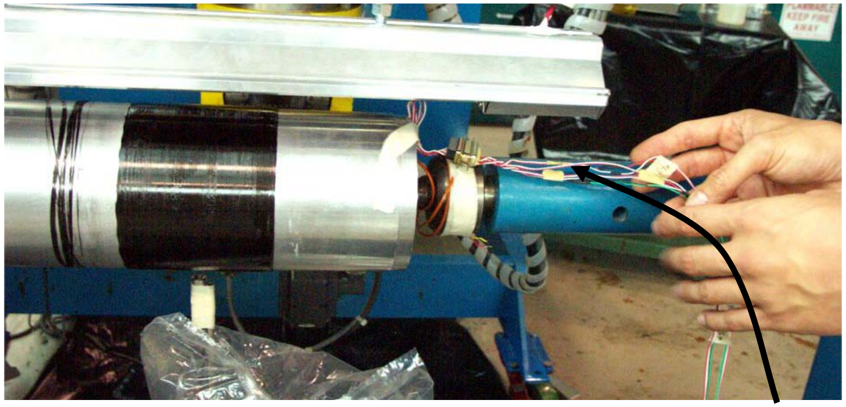


- Press-fit sheathing
  - more complex assembly
  - capable of high levels of pre-stress

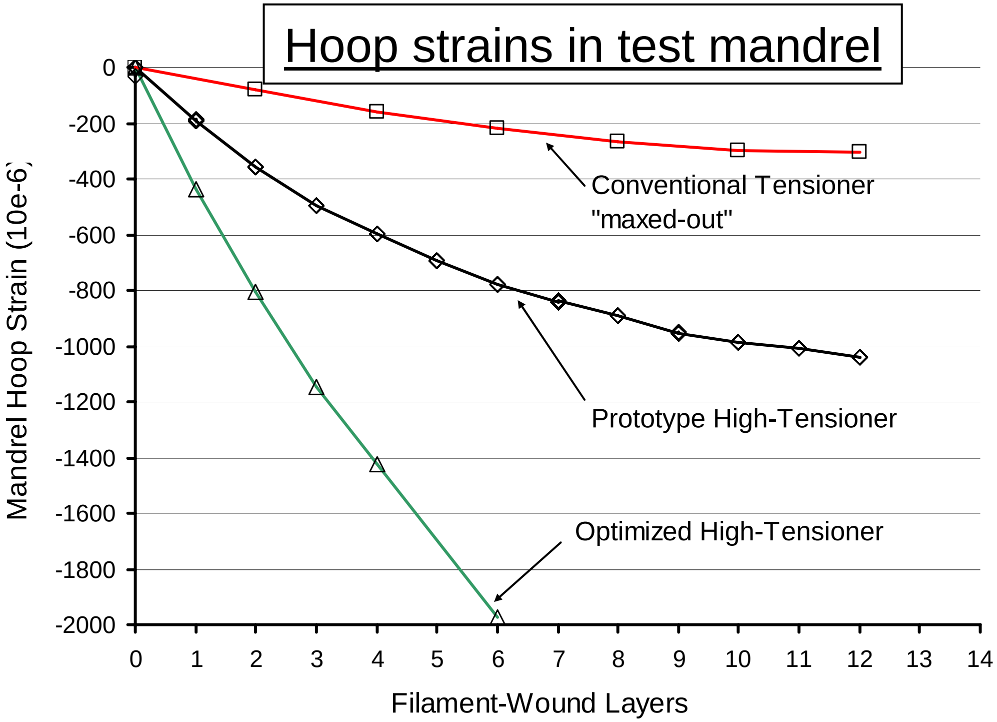


High-tension filament winding

- Can deposit T1000 at 1.2 GPa fiber stress
- Used to fabricate sheathed ballistic specimens

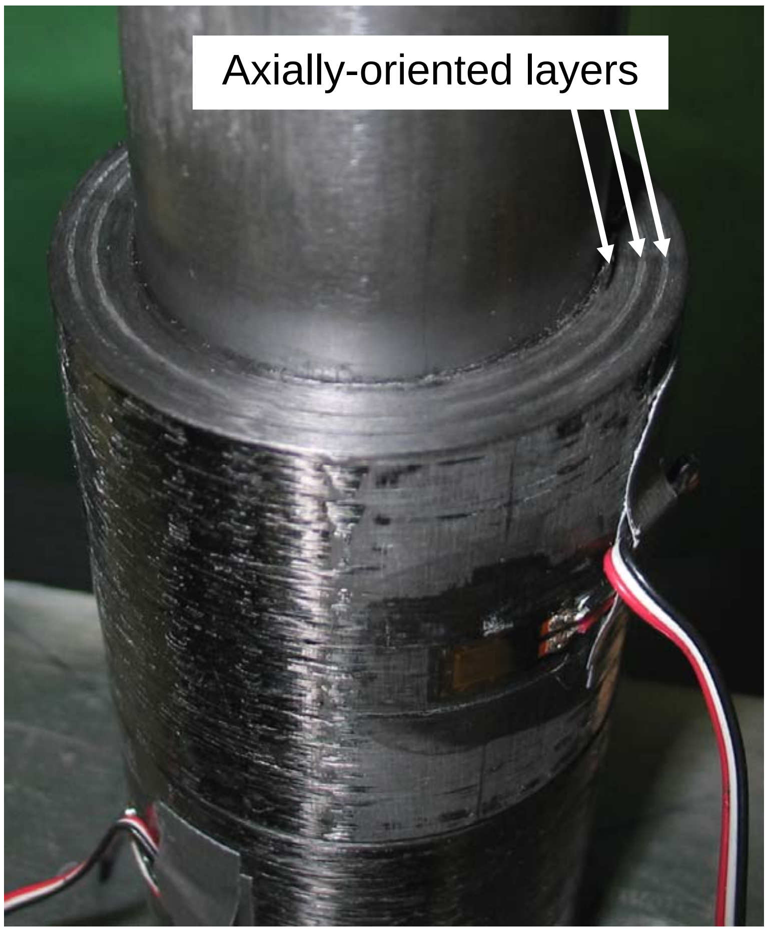


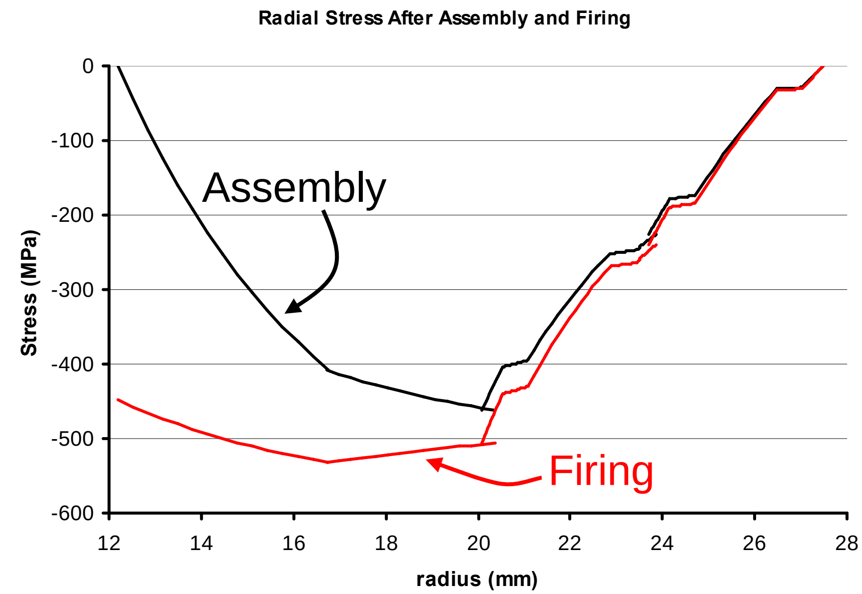
Strain gage instrumentation on ID of test-mandrel

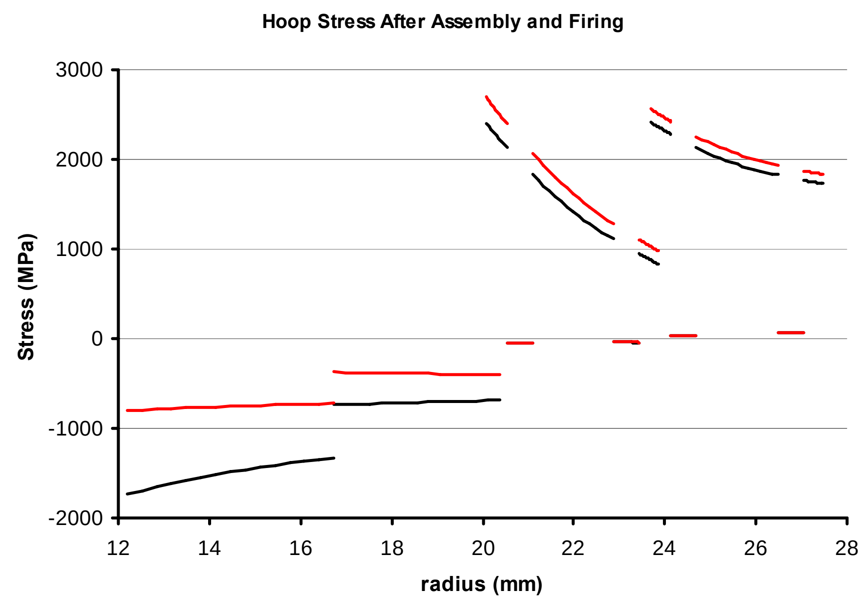


Press-fit investigation

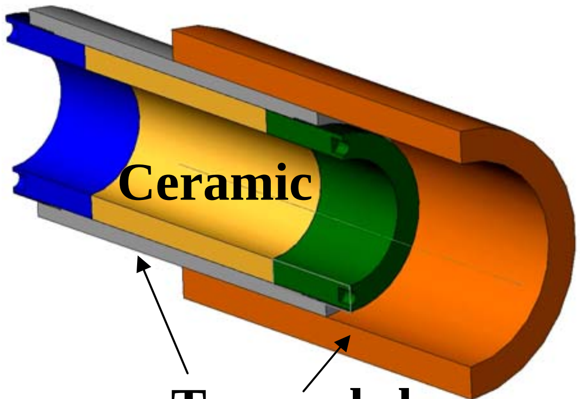
Layup sequence designed to achieve maximum thru-thickness strength



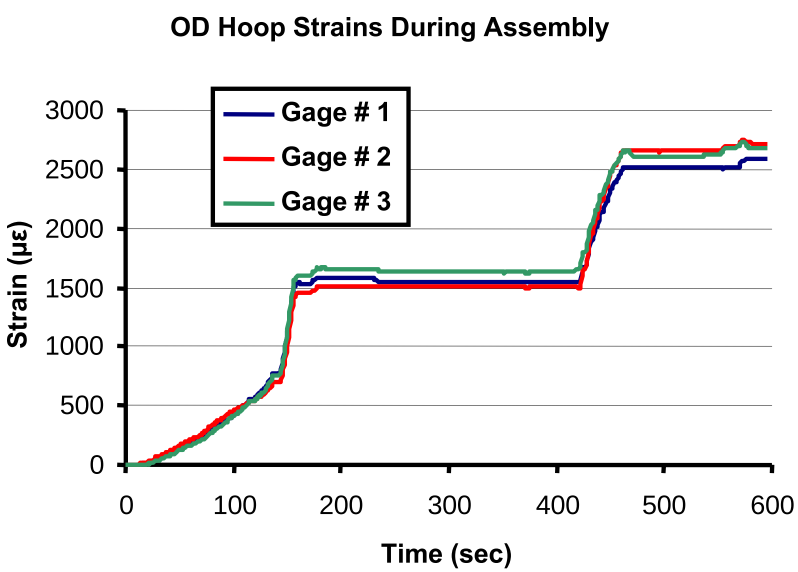


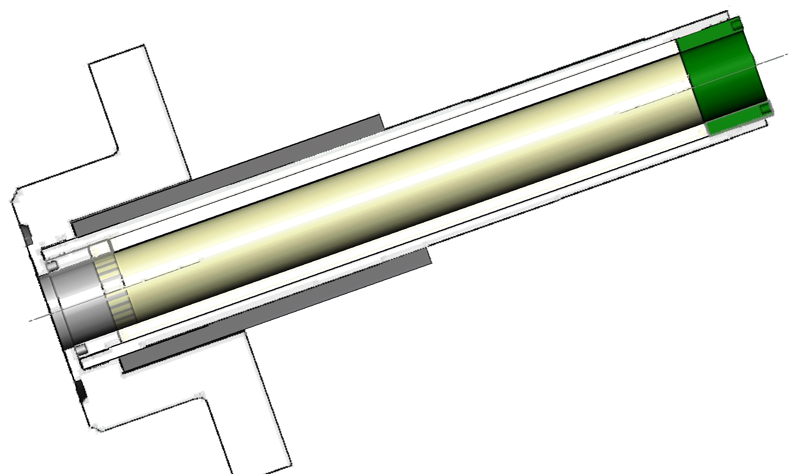


Multi-axial confinement uses press fit interference



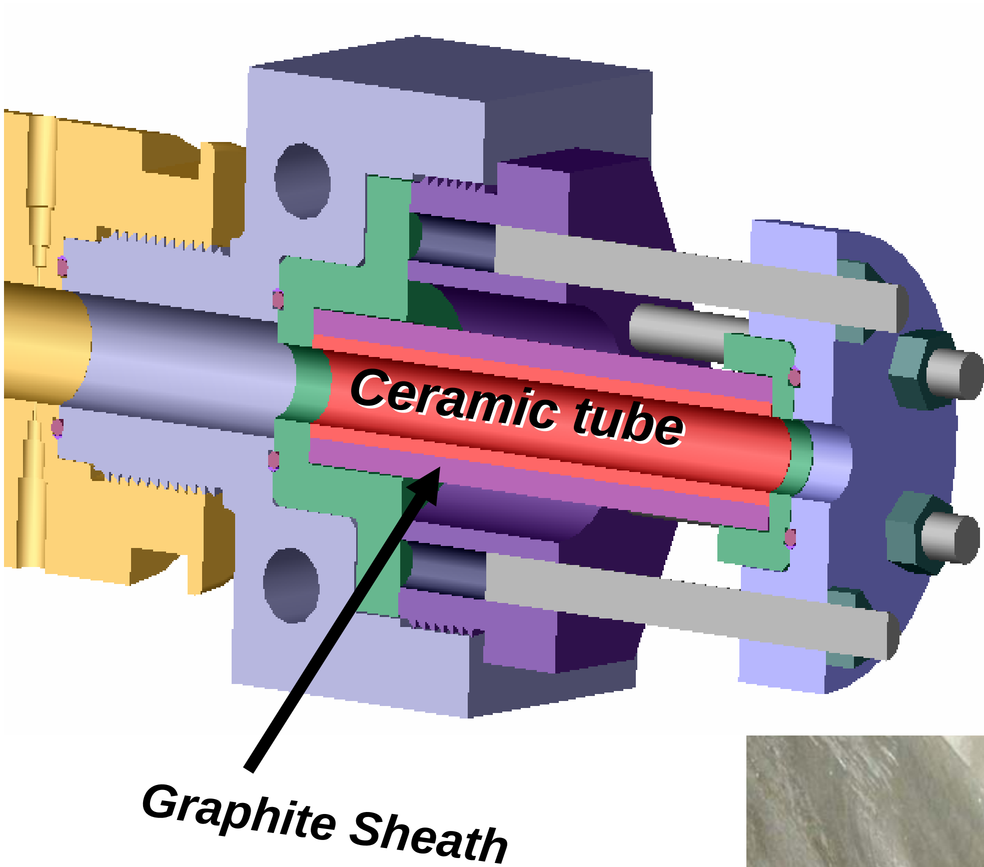
Tapered sleeves provide assembly interference





Demonstrated sheathing pressure in excess of 400MPa

A ballistic test fixture was designed to test overwrapped samples



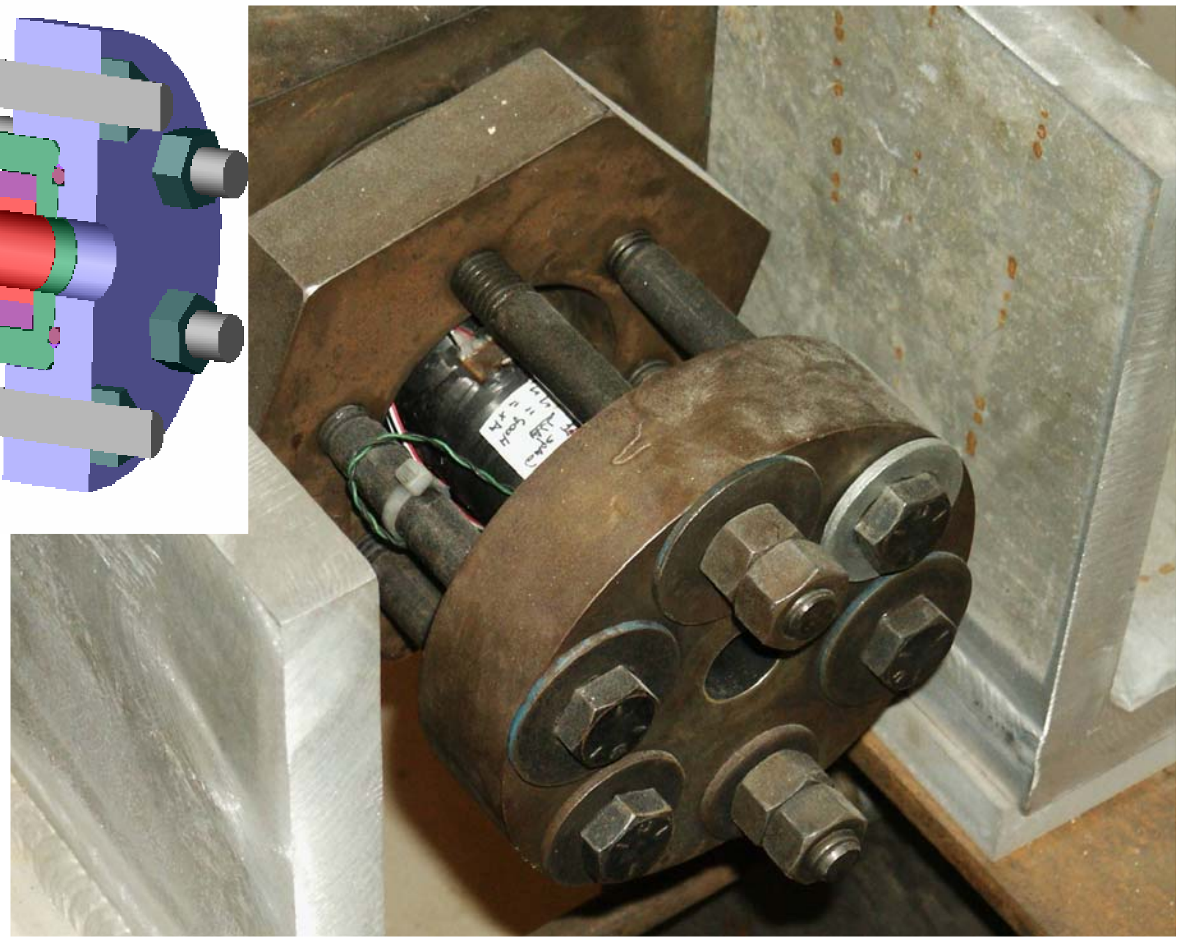
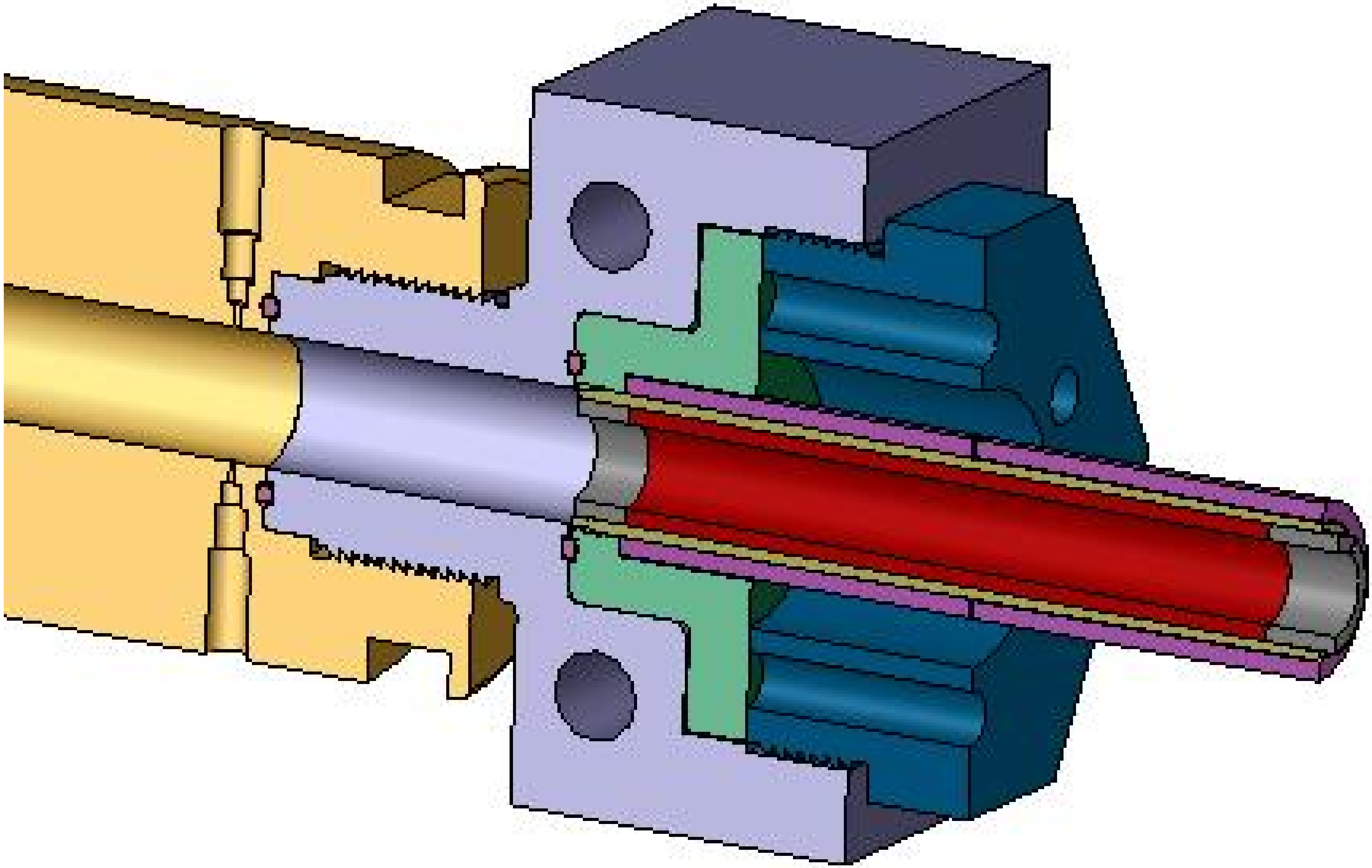
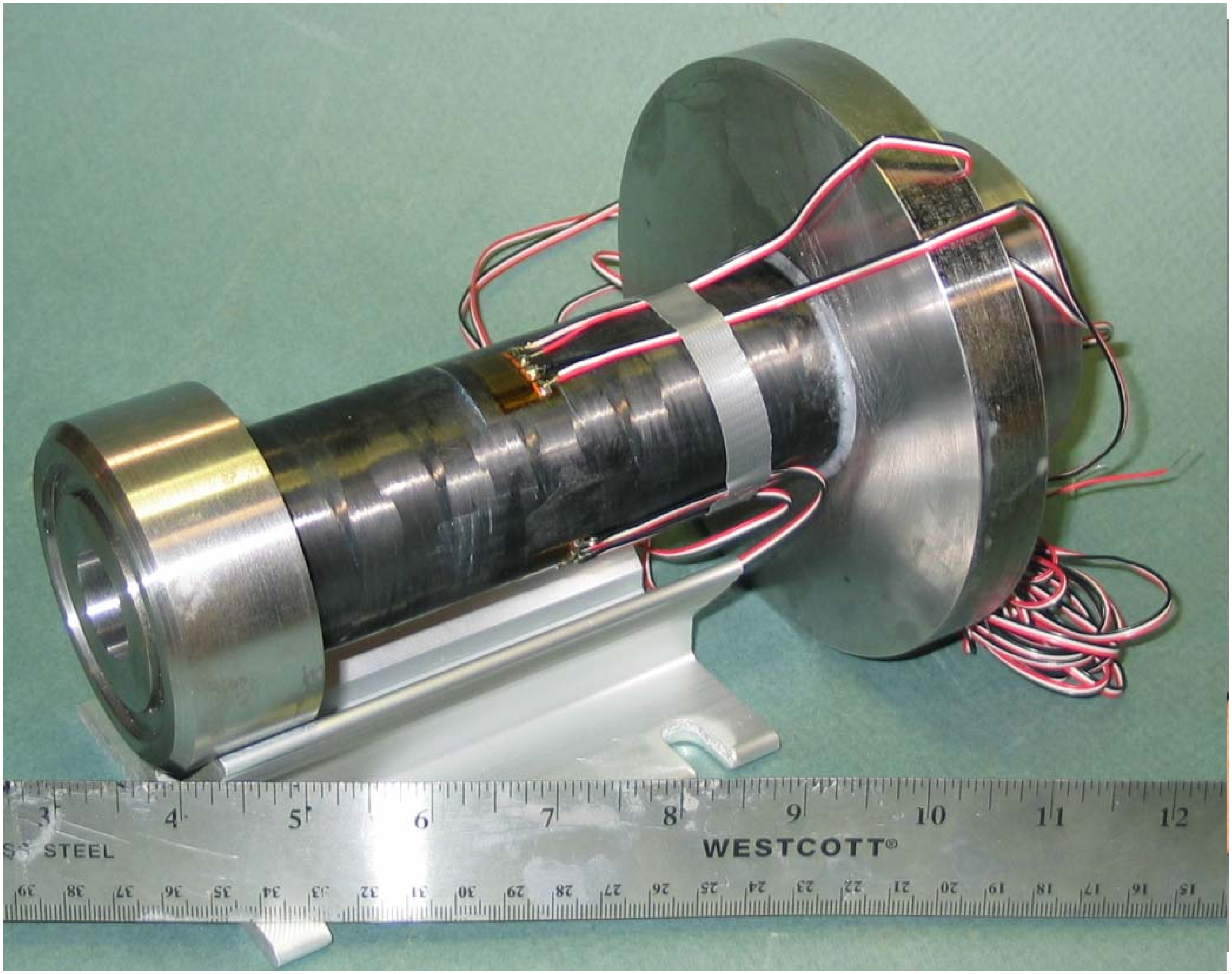


Illustration of cantilevered MAXCON installed in ballistic test fixture



Ballistic Specimens



Firing History & Plans

- Four Si_3N_4 tubes with high-tension wind
  - Maximum pressure achieved ~45 ksi
  - Ceramic tubes crack but failure is not catastrophic
- Two SiAlON tubes with high-tension wind
  - Maximum pressure achieved ~25ksi
  - Issues with tube concentricity and the firing fixture have limited the achievable pressure
- Test of multi-axial confinement scheme planned by year end

Summary

- Commercially available ceramics were identified as viable for ceramic-lined gun barrel applications
- Developed a probabilistic design approach to account for ceramic failure behavior
- Investigated robust sheathing schemes to provide the required level of compressive pre-stress
- Conducted preliminary firing tests with 25-mm tubes achieving 45 ksi (in line with predicted limits)
- Proof testing planned on a 65 ksi capable design in a 25-mm, cantilever cannon configuration